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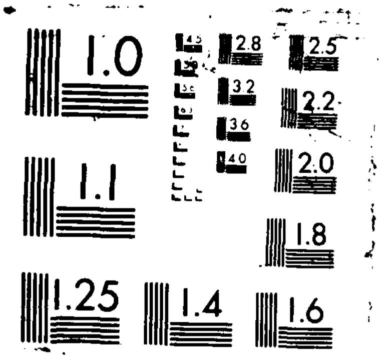
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Technical Memorandum

BIONIC MODELING OF KNOWLEDGE-BASED GUIDANCE IN AUTOMATED UNDERWATER VEHICLES

Date: 24 June 1987

Prepared by: Martha J. Guastella
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This memorandum describes the auditory localization behavior of the barn owl as an example of how bionic systems may be modeled for application to underwater vehicles. The nocturnal barn owl (Tyto alba) is unique in its passive localization ability, having vertically displaced ears with different peak sensitivities. It has an audible range of 0.1 kHz to 12 kHz and a sensitivity of -18 dB SPL. Despite its small size, it can get bearing, azimuth, and elevation without leaving its perch. It can localize pure tones almost as well as noise. Based on currently available data on the owl's sensory and structural capacities, a model of its localization behaviors is developed to identify the decisions and information needed in localizing prey. The informational requirements at each stage of its mission are projected from environmental and behavioral data. Guidance is shown as an automatic system based on nulling mechanisms; after the identification of the prey, decision-making is a go/no-go election. Sensory information is continuously

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updated by the owl while in motion until the final attack phase. The use of intelligence is discussed. This model is offered as an illustration of how bionic systems may serve to identify the kinds of information required by an autonomous underwater vehicle (AUV). It also suggests a model of sensors and decisions whereby localization occurs. Applications for AUV tasks are suggested.

ABSTRACT

This memorandum describes the auditory localization behavior of the barn owl as an example of how bionic systems may be modeled for application to underwater vehicles. The nocturnal barn owl (Tyto alba) is unique in its passive localization ability, having vertically displaced ears with different peak sensitivities. It has an audible range of 0.1 kHz to 12 kHz and a sensitivity of -18 dB SPL. Despite its small size, it can get bearing, azimuth, and elevation without leaving its perch. It can localize pure tones almost as well as noise. Based on currently available data on the owl's sensory and structural capacities, a model of its localization behaviors is developed to identify the decisions and information needed in localizing prey. The informational requirements at each stage of its mission are projected from environmental and behavioral data. Guidance is shown as an automatic system based on nulling mechanisms; after the identification of the prey, decision-making is a go/no-go election. Sensory information is continuously updated by the owl while in motion until the final attack phase. The use of intelligence is discussed. This model is offered as an illustration of how bionic systems may serve to identify the kinds of information required by an autonomous underwater vehicle (AUV). It also suggests a model of sensors and decisions whereby localization occurs. Applications for AUV tasks are suggested.

ADMINISTRATIVE INFORMATION

This memorandum was prepared in support of the Automated Underwater Technology Program at the Naval Underwater Systems Center and presented at the Fifth International Symposium on Unmanned Untethered Submersible Technology, on June 24,1987.

The author of this memorandum is located at the Newport Laboratory, Naval Underwater Systems Center, Newport, Rhode Island 02841-5047.

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INTRODUCTION

Bionics refers to the utilization of biological prototypes of life-forms whose structure, functions and mechnaisms provide design ideas for systems that might be used by humans. A common application is the use of robots to perform work in hazardous or inaccessible environmental areas where the use of human labor may not be safe. Other applications are in the design of sensory systems such as that used by the Sidewinder missile, which tracks and overtakes the hot exhaust of an aircraft, exploding in its tailpipe. That understanding of the heat-sensitive capability came from a study of infrared sensors of a rattlesnake, which can detect a heat change of 0.003° C that allows the snake to discriminate a tasty meal of rabbit from a sun-drenched rock of similar form (Davis, 1973). Another application came from studies of a frog's eye that led to the insight of how to amplify a signal while suppressing the background noise (Lettvin, et al., 1959). This particular work has been successfully applied to the design of a radar scope, a telephone filter, and soon to hearing aids. Many novel solutions have been derived from analogies to plant and human informational processing.

Recently, considerable interest has been directed at the development of expert systems and computer simulation to analyze thinking processes. However, some cognitive modeling tasks have become computationally intensive in the use of expert systems. Such systems require memory, time, weight, and power to generate solutions. Hence, it is worth considering the kinds of intelligence one needs to generate a task. Typically, expert systems are developed to mimic the thought processes of some human expert doing his task. The fundamentals are shown in figure 1 (from Nagy, 1985). The knowledge base contains all the rules and commands for solving problems that allows the user to reach the goal. Simply defined, an expert system is a set of inputs that gives

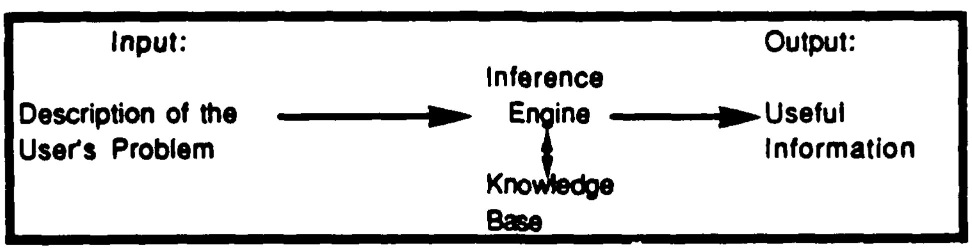

Figure 1. Basic Components of an Expert System (Nagy, 1985)

a description of the user's problems into some kind of processing system in order to get an output of useful information to achieve the task. The output is generated from the inference engine that combines information supplied by the user's answers to questions with rules in the knowledge base that are used to get new information to solve the problem or reach the goal.

In this memorandum my expert is the barn owl (Tyto alba), whose behavior has been demonstrated to solve the passive localization of an auditory sound source in its environment. The modeling of this behavior distinguishes decision-making (for which a knowledge base may be required) from guidance behaviors (which may be automatically governed by a nulling system). In living systems, the nervous system does not waste its computing resources in sensory or motor processing. When humans hear a sound coming from the side, they not only turn to that direction but their eyes are in focus for that distance too. The very young, the aged, the infirmed, and the intellectually impaired are all quite capable of navigating through an obstacle path towards a goal despite varying deficits. In fact, after learning a task, the brain delegates its control and guidance to lower levels of monitoring. There is great value in studying how neural motor systems operate in other species besides humans. Yet there is a natural tendency to compare systems in terms of human capabilities rather than consider the cost/benefits of each design model in terms of the task requirements under its environmental constraints of operation. Simplification and miniaturization are important design features, as well as specialization and redundancy of function.

This memorandum uses the acoustic data reported on the barn owl by a few investigators (Knudsen et al.,1979; Knudsen,1980; Konishi, 1973a, 1973b; Payne, 1971) to construct a model of the dynamic acts used in auditory localization for the purpose of understanding the passive localization of prey and to identify the possible decisions, the informational values, and the sensory structures that may be applied to guidance and localization in automated underwater vehicles (AUVs). While these references may look old, they do represent currently available data. The work of ethologists and those who study comparative psychoacoustics is often not a subject for sponsorship compared to others; but when you think about it, you'll see that an owl is a very efficient killing machine. Using what is known about the owl's sensory anatomy and its sensitivities, I modeled the behavior in terms of the task functions in the time

available and then considered the cue values needed at each stage of the mission. While much of the data come from beginning investigations that used tones and clicks to correlate with behavior, it is important to use the environmental sounds for a real understanding. Audiograms are used to measured hearing sensitivities, but it is clear that our communication depends upon the processing of the more complex tones of speech (Stebbins et al., 1984).

This method considers the sound sources used by the owl, which is noise at various bandwidths, e.g.,the rustling of leaves made by a small rodent. The owl also uses the rhythmic tonals of a moth's wings in flight, but it does slightly better with noise bandwidths. The features of the method are summarized in figure 2.

- o This report does not describe the design of a guidance system for an AUV but suggests how bionic models may offer ideas for AUV designs.
- o The method used is to model the actions and decisions needed by a barn owl to localize its prey.
- o The method focuses on the cue values and the environmental data in the timeframe for action.
- o The report attempts to raise questions regarding the decisions and processing capabilities for understanding the decisions of barn owls and the informational requirements for this phase in AUVs.

Figure 2. Methodological Approach

DESCRIPTION OF BARN OWL

AUDITORY ABILITY

Nocturnal predators are known to have a keen ability to localize the sounds of their prey. Compared to how humans localize sounds, these birds and certain fish are all the more remarkable because they must constantly localize their prey in azimuth and elevation while they are in motion. When humans detect a sound source coming from either side, they automatically orient in the direction of the sound source based on an

intensity discrimination, and their eyes are automatically focused for that distance. Because of their small interaural size, birds detect the onset of the sound source to each ear; how they distinguish phase is not well known. One of these nocturnal birds that does remarkably well at passive auditory localization is the barn owl(Tyto alba), for which sufficient behavioral and anatomical data have been collected to justify modeling and a theory of sound localization. The owl's soft downy feathers hardly make any sound as it swoops down through the air towards its prey. It dives on its victim with extended talons and an open mouth by which it swallows a mouse or rat whole and later brings up small balls of fur and bone.

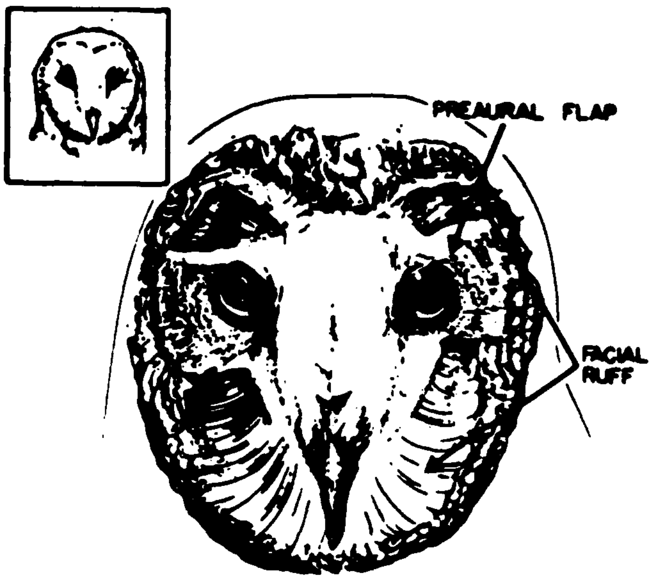

Figure 3. Front View of Barn Owl's Face Without His Ruff (Upper Lefthand Corner Shows His Normal Appearance) from Knudsen, 1980 (Reprinted by permission of publisher)

RANGE OF ACOUSTIC SENSITIVITY

The barn owl is particularly unique among birds in its ability to localize sound. Behavioral experiments have shown that even without specialized auditory systems, barn owls can define within 1° of azimuth and elevation in different spatial planes,

which allows them truly superior localization (Payne, 1971; Knudsen, 1980; Konishi,1973a,1973b). Figure 4 taken from Knudsen's (1980) and Konishi's (1973b) compares the barn owl's range of frequency by intensity (solid curve) with that of some average sixteen song birds (indicated by the dotted curve). Notice that the average songbird has a range from 0.2 kHz (200 cps) to about 8 kHz and is most sensitive in the range of 2-5 kHz. The barn owl's range is from 0.1 kHz to about 12 kHz and at its greatest sensitivity, its threshold is about -18 dB. (Reference is 0.0002 dynes/cm ^{2}). The dashed line shows how quickly the owl's range falls off at the higher frequencies. Notice that the owl's sensitivity is considerably better than the average songbird by about 25 dB across the range and that its most sensitive range is between 1 and 12 kHz. Also notice that the barn owl appears to have two areas of maximum

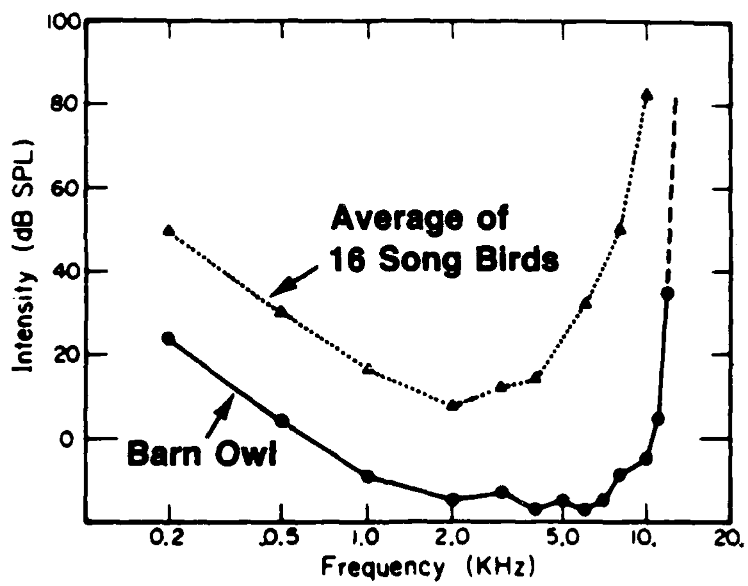

Figure 4. Comparison of the Range of Sensitivity in Frequency and Intensity for Songbirds and the Barn Owl (From Knudsen,1980; Konishi,1973b) (Reprinted by permission of the publisher)

sensitivity, one at 4 kHz and the other at 6 kHz. At the time these data were published, the existence of critical frequencies for each species as an alarm frequency might not have been known; the differential sensitivity of each ear was definitely not known. The significance of this difference is curious and worthy of further investigation regarding

how it operates to serve the owl so well. This will be discussed later. It should be noted that the owl's prey are small rodents, birds, and bugs and their foraging movements are heard by the sound of rustling leaves or rhythmic wing beats.

ASYMMETRY OF EARS

The faces of owls have captured the fancy of artists as well as others for their expressiveness. The owl's eyes are located in a symmetrical horizontal plane. Since the owl hunts at night in darkness, its eyes are most functional for form and motion detection. What makes an owl look unique is that characteristic ruff of feathers that go vertically from the mid-sagital plane around the outer frame of the face and under its jaw. The feathers in the ruff can be oriented in direction by muscular control. These feathers may serve to capture sound, very much like a tuned antenna and funnel it into the ear. The height of these facial ruff feathers is 6-8 cm, which corresponds to the wavelength width of about 4-6 kHz. When the ruff is removed, these discriminatory sensitivities are impaired. Figure 3, taken from Knudsen (1980), gives a picture of the barn owl with and without its facial ruff. The owl's normal appearance is given in the upper left-hand corner.

The ears are located above the eyes, about where the human's eyebrows are, under a flap of skin that protects the vertical ear holes that tunnel into the skull. What is distinctive here is the fact that the barn owl's ears are not symmetrical. There are about 139 different species of owls and, in 39 that were studied, only 9 had asymmetrical ears. In the barn owl, the right ear is elevated relative to the left ear by about 15^{o}, sitting about 1/2 inch higher than the right (Knudsen, 1980). While the spatial difference between the ears for average songbirds is about 2 cm, for the barn owl it is 4.8 cm along the horizontal plane. The right ear also peaks in sensitivity at 6 kHz, while the left ears peaks at 3-4 kHz. Since the ears are in the frontal plane of the face above the eyes, this means that differences cannot be gotten from head shadow as in humans.

ELEVATION AND AZIMUTH RANGE

The barn owl has a horizontal range of 80^{o} (40^{o} on the left and right of center) and it can discriminate $1\text{-}2^{o}$ in azimuth and elevation as well as mammals. Both ears are

equally sensitive to low frequencies below the owl's horizontal plane at elevation (0^o). This accounts for the owl's listening posture, perched high in a tree above its territorial domain. Its directional abilities are greater than other birds. As the sound source goes from 3 kHz to 6 kHz, this frontal horizontal plane increases based on the frequency-dependent rotation of the owl's ear. This is believed to be important in localization.

Above 5 kHz, the directional sensitivity of each ear to the sound source drops off so that the high frequencies are detected by the left or right side closest to the source. This means that there is no neural crossing of the signal processing in the owl brain above 5 kHz. In humans, information from one side is also fed to the other half of the brain and there is a slight cost of time for this shared input. This information on frequencies above 5 kHz is important to the computation of time of onset of the sound signal to the respective ear.

PHASE DIFFERENCES AND TIME OF ONSET

Phase differences are normally the result of two different path lengths taken by the same acoustic signal as received by human ears. But since the owl's ears are up front and close together, the owl will not be getting this kind of phase difference. During motion, the owl will get Doppler shifts in frequency. Time of onset is relevant for noncontinuous signals or if the owl had a way of interrupting the signal it receives. It can also cross-correlate between left and right.

AUDITORY PARAMETERS USED IN SOUND LOCALIZATION

By virtue of the different bandwidths of sensitivity afforded by the left and right ear and the detection of onset time, the owl can localize a sound source without moving. The barn owl has binaural and monaural cues as well as cues that operate in relative motion when either the target or the owl moves. Table 1 lists the cues.

Table 1. Sound Localization Parameters Used by the Barn Owl
BINAURAL PARAMETERS:
1. the difference in onset time of the sound source to each ear
2. the difference in phase of the sound source to each ear
3. the difference in sound intensity to each ear
4. the difference in frequency to the left and right ears
MONAURAL PARAMETERS:
1. frequency changes
2. intensity changes by scanning of the head
MOTION PARAMETERS:
1. Doppler shift in frequency at each ear
2. Changes in onset if sound is of intermittent duration
3. Changes in phase difference of sound of longer duration

The model of the simulated action of the flight allows the consideration of what parameters are utilized in the time and space available. It is the dynamic mode that is of major concern here.

STRUCTURES FOR AUDITORY LOCALIZATION IN THE BARN OWL

Knudsen (1980) has shown three structures of sensory information used in localization that allows the barn owl to detect a sound source even before the owl moves from his starting position. The barn owl can passively triangulate on its prey by moving its head in azimuth and elevation. In this manner, the head is moved to null the differences in intensity of the frequency at each ear and the onset time of the frequency to each ear. Konishi (1973b) had found that the intermittent sound had to occur at least 20% of the time for the moving owl to accurately strike its target. These data have been redrawn for greater clarity in figure 5. Figure 5 assumes that the sound source is 8 kHz to the right ear and 3 kHz to the left ear. The owl orients itself to null the difference in intensity between them. Since the ears are in the frontal plane, there is no phase difference caused by head shadow. Also, since the typical sound source is intermittent rather than continuous, the importance of phase differences is less while the owl is stationary. However, when the owl is in flight, phase differences may be a very valuable cue as I will develop later. Onset time is given in the vertical column at the center of the graph. The triangulation of all three factors is indicated by the blackened area where localization is targeted.

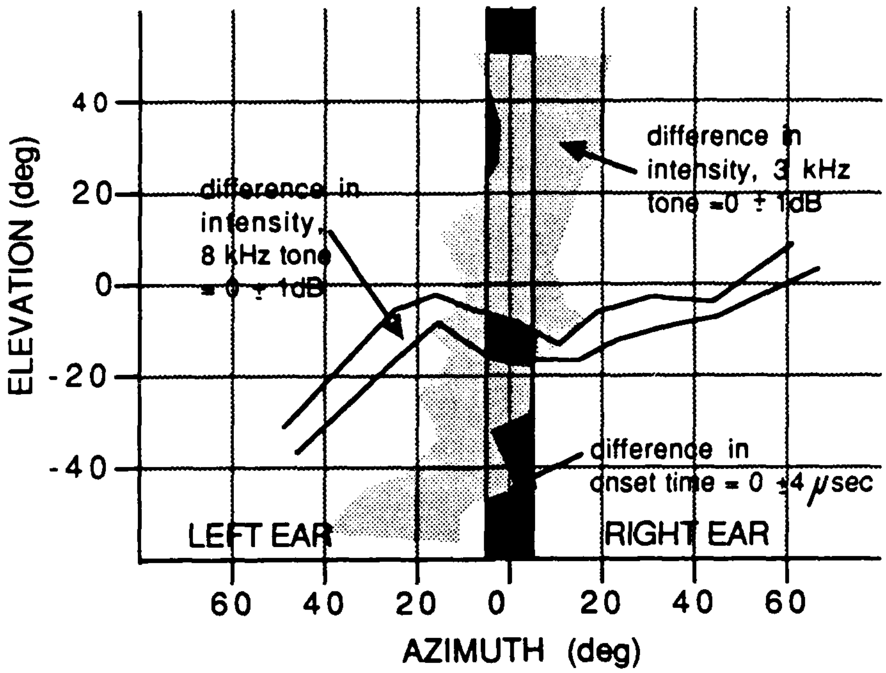

Figure 5. How the Barn Owl Localizes His Target by Nulling Frequency, Intensity, and Onset Time to Each Ear (Triangulation is shown by the blackened center where overlap of the values occurs) (Redrawn from Knudsen, 1980) Reprinted by permission of the publisher

As the owl proceeds in transit search, it orients its head to null the difference in intensity between the ears. The onset time between the left and right ear is also nulled by the owl and where each of these factors coincide is given at the point on the figure that is filled in black. As the owl moves down toward its target, it continuously orients its head and body to align itself with that of its prey as it homes in on the target.

MODELING OF BARN OWL'S LOCALIZATION BEHAVIOR

DESCRIPTION OF THE INPUTS

Based on my analysis, I'm proposing that the owl processes the information in the manner indicated in figure 6, and there are only two levels of control. Sensory

information is sent into a higher level of control, decision-making, which results in a decision to flight or abort its mission. It is a go or no-go type of decision. But, sensory information is also sent to a lower level of guidance, which results in automatic adjustments done without any great thought.

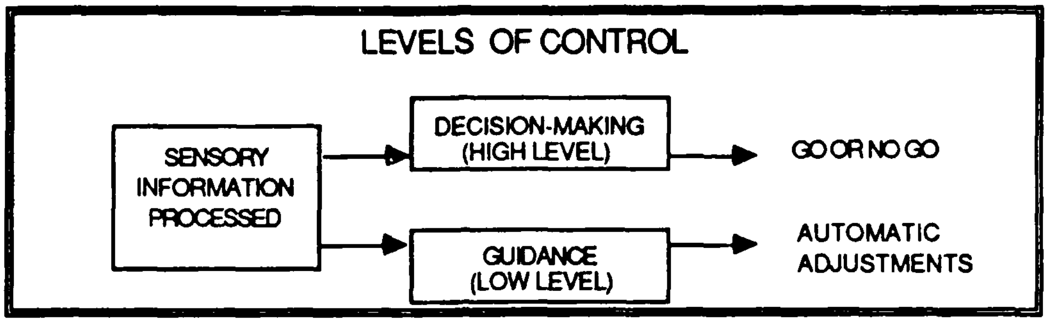

Figure 6. Levels of Control in Sensory Information Processing

The input is any noise spectrum within the frequency range of the owl. The noise is received by two sensors, left and right ears. Immediately on detecting the sound by its two asymmetrically placed sensors whose frequency sensitivity peaks at 6 kHz for the right ear and 3 kHz for the left ear, information is gathered on (1) the frequency of the noise emitted by the prey, (2) onset time of the signal to each sensor, (3) phase differences between the ears, and (4) intensity information (but not clear on range data).

DECISION PHASES IN LOCALIZATION PROCESS

A model of the action flow diagram is given in figure 7, starting from a stationary position down to the diving attack phase. The actions are drawn on the left side and the decision phases are given on the right.

1. DETECTION OF SOUND - The owl detects a sound source from his stationary perch. By moving the feathers about the ears and head assembly, the owl attempts to orient to the signal in frequency and intensity and by nulling the difference in onset time in both ears, maximizes the signal. This discriminates left/right and up/down information.

2. DISCRIMINATION OF PREY - The next decision is to discriminate whether or not this is prey. In a memory of acoustic features, there would be a range of frequencies to identify, e.g., mouse noises, moth wings flapping (tonals), rat noises, etc. Intensity information is combined with a shift in frequency. If the prey moves, this may give a clue. If the acoustic signals are identified and acceptable, the owl starts its transit by swooping down on its prey. If not, the owl waits for another noise to discriminate. This is essentially a recycling loop.

3. COMMITMENT TO TAKE ACTION - Once the sound source has been identified and accepted, the owl begins its swoop in the direction of the sound. The owl takes advantage of gravity to swoop toward its prey, processing frequency data, onset time, and intensity information as it moves. From here on, the problem is a relative motion,one between the owl and its prey. A dynamic model is very heuristic in identifying the information needed and what questions need to be answered in understanding this task. The owl constantly updates its information correcting azimuth and elevation to maximize signal strength. If the swoop is interrupted by a change in information, e.g., an alarm signal is introduced, then the owl returns to start to recycle the process or it reorients its position in flight.

If the swoop is not interrupted, it continues to process onset time, frequency, intensity, and phase differences. Onset time is very important, but it is not used in this decision but rather as a steering mechanism for piloting.

What is the status of the prey? This depends upon the movement of the prey. After the initial launch transient, the owl swoops at a constant velocity resulting in a prey-dependent Doppler shift. If there is no movement by the prey, there is no extra movement in the Doppler shift. If the owl is decelerating, there is a decrease in the Doppler shift.

During this pursuit phase to the target, should the target move, the owl's path has to be changed by reorientation, i.e., a change in angle of elevation, azimuth, and bearing. If the target is running away, the elevation should increase. If the target is running towards the owl, the declination should increase. Supposedly, the attacking owl makes no audible sound as it comes through the air, and a fleeing prey, if it is aware of its peril, will run in a straight line to avoid being caught. The owl adjusts in azimuth and elevation by onset time up to the point where the change or difference in onset is above the discrimination threshold. As the owl gets closer to its prey, the prey's noise intensity should be increasing.

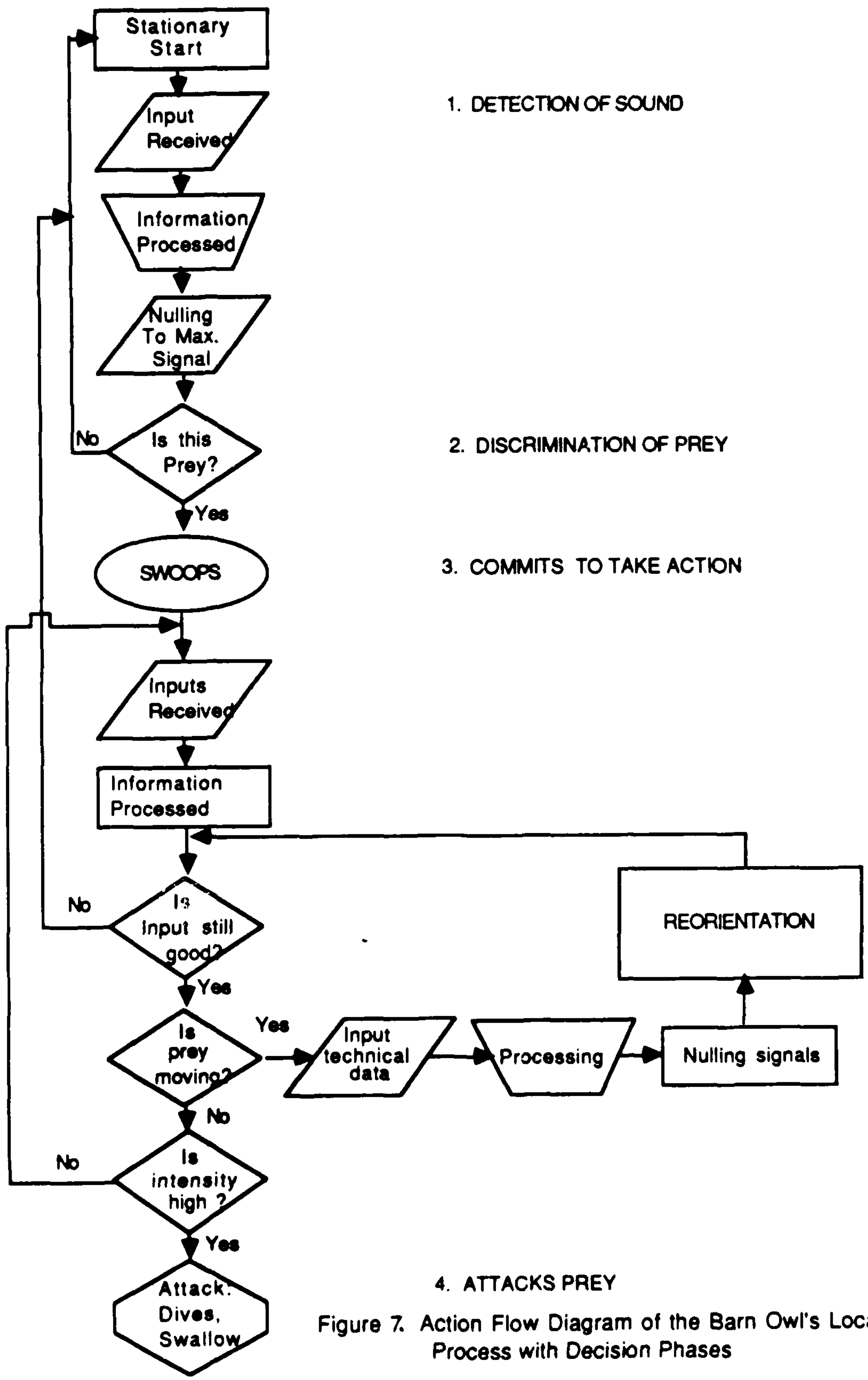

Figure 7. Action Flow Diagram of the Barn Owl's Localization Process with Decision Phases

4. ATTACK PREY - When onset time is no longer effective, and intensity reaches its maximum, the owl makes its decision on the difference in (1) the changes in intensity, (2) possibly the individual Doppler effect of each ear as developed later in table 2, and (3) possibly from distortions, such as beats or a difference tone. Recall that there are two different amplitudes by virtue of two different sensitivity peaks in each ear as well as differential Doppler. So the rule should be a tradeoff between these two rules. The knowledge base is both instinctual and learned. The owl's tactics would be associated with the inference engine.

The decisions involved in the attack of the prey are actions that can no longer be aborted. When the intensity reaches a certain range or level, the owl is committed to attack. Data show this dive distance to occur at about 2 ft (60 cm) from the sound source (Konishi, 1973b). It is primarily associated with the sound source rather than sight. At this point, the mouth opens, the head goes back, the eyes shut, and the talons are extended. There is a windup and cupping behavior as the owl lifts its prey to its mouth. This is probably an instinctual response that is hard wired. When you consider the size of the talon openings, one gets a notion of the aiming accuracy.

Figure 6 shows that the sensory information is received in parallel with the decision-making level and the guidance control level. Guidance inputs result in automatic adjustments of the body orientation to maximize the signals from the source. The head of the owl is aligned with the head or sound source of the prey so the grasp is on the body and the owl can snap the prey's neck most easily. The decision to be made after detection and discrimination is whether or not to commit to pursuit. Once committed to pursuit, the owl's navigational guidance works automatically unless there is a change in input data or an intervention such as an alarm situation that might occur. When the guidance system is separated from the decision-making system, the decision-making is relatively simple and straightforward.

CUE FACTORS AT EACH STAGE OF LOCALIZATION

The detection stage depends upon the range and sensitivity level of the sensors. These can utilize monaural and binaural cues. The environmental signal is a sound source, generally a wide spectrum bandwidth noise but it could also be a pure tone as well. The sound source will have a frequency spectrum, an intensity, and (from the onset of the spectrum to each ear), a bearing. Range may be obtained from the intensity, but there may be other kinds of processing possible that are not yet known.

The discrimination stage depends upon the past experiences and memory of the animal. The need state of the predator may influence its curiosity to explore new sound sources. However, the same cues in the signal as in the detection stage are important .

The commitment to flight depends upon the owl's need or mission requirements. The decision is a simple go/no-go one, and then guidance is automatically governed by the nulling of the various factors described earlier. Doppler may be seen as important in this phase, but, from the typical signal source, one may suspect that difference tones are more important. To understand how these tones are processed, one needs to look beyond the respective ear drums of the owl to find that they share a common air space and coupling chamber. How this works to encode the signal in the nervous system is not understood. How this common chamber affects the resultant tone can be simulated though. While frequency and intensity cues may be initially important to detection and discrimination, they are less important to this stage. Onset time for an intermittent sound is useful if it supplies a signal at least 20% of the time (Konishi, 1973b); otherwise, accuracy is poor. Phase differences from a continuous source would be less common even if the owl itself is in motion. But phase differences induced by the owl in flight appear to be significant. While the owl homes in on its target in a most economical flight path, it is constantly verifying its sensory inputs to see whether the target is still viable and/or if there is any reason to abort the mission. The owl listens to its signal source as well as background sounds. Guidance is automatically adjusted to the sound source and body orientations follow directly. If there is any real threat, the owl can return to its initial position; but, if all follows on course, the owl's sensory signals have leveled off at their maximum and the next stage is an irreversible attack. Here, the owl reaches the nadir of its path and his sensory cues. There can be no other plan but to attack and dive.

At the attack phase, all previous cues have been confirmed in the flight thus far and intensity appears to be the primary cue. Perhaps the intensity of the source has reached a steady-state signal. The owl's behavior is instinctive here and there is no time left to abort the attack. Vision has not been shown to be a factor but it is a possibility. There is some evidence that the owl shuts its eyes before striking its prey (Konishi, 1973b). But it is clear that the animal can learn and after a few unsuccessful strikes, it may simply have to open its eyes in more ways than one.

THEORETICAL SPECULATIONS

There are several interesting speculations that this analysis raises for explanation and further investigation: (1) the role of Doppler and difference tones; (2) the role of the asymmetrical ears and how they process the signal; (3) the role of the differentially peak sensitivities in each ear; and (4) the ability to localize from wide noise bandwidths better than pure tones.

DOPPLER AND DIFFERENCE TONES

While the speed of the owl and other birds has not been adequately documented, Konishi (1973b) reports owl's flight in captivity during one of his experiments at about 4 m/s, but he notes that it can probably fly faster. Table 2 shows the effects of Doppler defined as the apparent frequency of a sound wave train produced by the motion of the source toward and away from a stationary observer (or vice versa). Applying the formula of the observed frequency, F_0 in cps, where v = velocity of sound in the medium, v_0 is the velocity of the observer, v_s is the velocity of the course, w is the velocity of the wind in the direction of the sound propagation, and F_s is the frequency of the source, Doppler has been computed as :

$$F_0 = \frac{V+W+V_0}{V+W-V_s} F_s \;.$$

For simplicity sake, I am assuming that there is no wind and that the prey is stationary.

For each speed of the owl's flight from 5 mph (or in m/s) to 40 mph, the observed frequency change is computed for a 4-kHz, 6-kHz,and an 8-kHz tone, and the percentage change is also given. The relative percentage change is naturally always the same regardless of frequency. But the higher the frequency band, the further the absolute downshift in frequency. I think it is not unlikely that an owl can fly or swoop at 20 mph and the resultant changes appear to be significant for guidance. Whether it is the absolute change or the relative change in frequency remains to be determined.

Table 2. Computed Doppler Shift for 4-, 6-, and 8- kHz Sounds as a Function of Barn Owl's Speed of Approach to a Stationary Sound Source and the Percentage Shift in Doppler

Barn Owl's Flight Speed		% Shift in Doppler	Change in Freq. of a 4000-Hz Tone	Change in Freq. of a 6000-Hz Tone	Change in Freq. of a 8000-HzTone
5 mph	(2.23m/s)	0.68	4027 Hz	6041 Hz	8054 Hz
10 "	(4.47 ")	1.35	4054 "	6081 "	8108 "
15 "	(6.70 ")	2.03	4081 "	6122 "	8162 "
20 "	(8.94 ")	2.70	4108 "	6162 "	8216 "
25 "	(11.17 ")	3.38	4135 "	6203 "	8270 "
30 "	(13.41 ")	4.05	4162 "	6243 "	8324 "
35 "	(15.64 ")	4.73	4189 "	6284 "	8478 "
40 "	(17.88 ")	5.40	4216 "	6324 "	8432 "

Another consideration here is whether or not distortions due to phase differences can offer further information to the owl. While small differences in frequency can result in beats that produce periods of quiet and then amplification up to 4 times the intensity, this does not appear to be operative for difference in frequency sensitivity at each ear for the barn owl. However, when the difference between two sounds is large enough so it can be heard as an audible frequency, this difference tone may act as a cue. For example, the difference in peak sensitivity between a 4-kHz tone and a 6-kHz tone is 2 kHz,and the barn owl may use this information as it homes in on its prey. What is even more fun to speculate about is how the owl captures its signal. It has already been pointed out that the owl can tune its feathers around the ear to capture sound; but it is even more intriguing to speculate on the function of having ears where humans have eyebrows. Of course, in that location the owl can close down his ears in a wink, so to

speak, and this explains the circular muscular fields around the ear flaps. What would that do to the sound? It would bring onset time under the control of the owl if the signal was continuous rather than intermittent. It would act like an acoustic parallax between the ears and that might be the important cue for localization. It would also serve to chop the signal or perhaps sample the signal. All of these considerations require further investigation. I don't know of any other animal that can close its ears down at will during the localization phase.

THE ROLE OF ASYMMETRICAL EARS

If the ears were located in the horizontal plane, as in humans, that would only give the owl a left/right discrimination capacity. If the ears were aligned in a vertically displaced plane, that would give an up/down discrimination capability. However, having ears displaced horizontally and vertically on a diagonal as the barn owl has, gives a very simple up/down, right/left discrimination capability so that any head movement is immediately translated into positional information. It is very simple but efficient.

THE ROLE OF ASYMMETRICAL PEAK SENSITIVITIES IN EACH EAR

The utility of having two ears of equal range of sensitivity but of unequal peak sensitivity can be thought of by analogy to the eyes. It would be as if you had two eyes that had identical ranges of sensitivity along the red to violet spectrum but with one eye that was most sensitive to say yellow light, and the other most sensitive to say blue light. Now by closing one eye, you would get the peaks of yellow in the environment and by alternating to the other eye, you would get the peaks of blue and these could be compared. But if you kept both eyes open, then you would get the sum of reflected light and the additive properties of yellow and blue are green, which is the most common color in our environment. Only now you would get a wider spectrum of greens and probably a flatter spectrum of greens than you would get with either eye that had identical peak sensitivities at green. By being able to shut down one eye at a time or use both, the owl gets a three-position switch on its nervous system where it can compare yellow, blue, or greens successively.

ABILITY TO LOCALIZE WIDE FREQUENCY BANDWIDTHS VS. PURE TONES

The barn owl does slightly better with wide noise bandwidths than with tonals. It

seems to need the higher bandwidths too. There is some interesting data on the owl's ability to do this but I believe I have speculated enough so far to justify my employment of bionic modeling. But for now, let me summarize what I have presented here today and let you consider its merits. In figure 8, I have attempted to highlight some of my approaches and their payoffs.

- o An action flow diagram and the decisions required have been modeled in the simulation of a barn owl's pursuit of prey.
- o The method of bionic modeling is offered as a tool for the study of sensory and environmental cues for defining the informational requirements at each phase of action.
- o It provides a way of testing design efficacy.
- o It identifies hierarchies of sensory motor processing that can be extended to the realm of navigation, guidance, etc., so that essential decision-making can be done more simply and without extensive computation.

Figure 8. Summary of Main Features of Methodological Approach

APPLICATION TO AUTOMATED UNDERWATER VEHICLES

The application of a bionic model to AUVs has much to offer beyond this entertainment on barn owls. The barn owl's auditory localization achievements of triangulating on a target is worthy of our attention when one considers this is done without moving from its stationary perch. Exactly how this is done should be a subject of further study and simulation. There are other bionic forms that are also worth considering in this regard, e.g.,the marine pinnipeds, sharks, etc., who have directional hearing and vision and use electrical ion sensing at their rostral surfaces to identify their prey. But the barn owl has this long-range capability of triangulating and identifying noise spectrums better than pure tone signals which it can do almost as well. Just how it correlates this information considering its simple inner ear ought to be considered further. There has to be some utility in the peak frequencies observed at each ear, especially since not all owls have this characteristic. Further, just as the study of

the frog's eye led to a method of separating signal from background noise, the study of the owl may show how noise bandwidths can be used to get at the signal source.

The technique of modeling bionic forms in certain phases of their functions offers a useful methodology to identify the efficacy of the signals and informational cues needed in the process. Intelligence can be considered in terms of decision-making as well as in terms of built-in hierarchies of sensory motor capabilities. In order for an AUV to accomplish its mission tasks, it needs to detect certain information and make certain judgments to take action or seek further information. While algorithms can be developed to direct these decision processes, such systems are costly in power, space, and memory. It is necessary to distinguish capability from intelligence, however. Viewed in this manner, decision-making can be separated from other action-oriented systems and really made very simple. It makes little difference whether the decision-maker is sitting in a manned or unmanned vehicle or is remote from the scene for that matter. The decisions are very much the same. However, the repertoire of capability built into the other systems, such as guidance, navigation, and other actions can be achieved through fairly well known control principles so as to simplify the task. Intelligence should not be equated with capability. We have all encountered capability without intelligence, as well as intelligence without capability. It remains for the trainer or the systems designer to specify the sequence and hierarchy of sensory motor relationships for which certain actions can be taken.

Effort should be directed at identifying the hierarchy of sensory-motor (effectors) that can be monitored at lower levels of control. When that intelligence is built in, the decision-making aspects are really quite simple and straightforward. The decisions are all the same.

The parallel processing of information can afford a complexity of behaviors, but decision-making need not be considered beyond the actions comprising the task. Whether a vehicle is manned or unmanned, the same kinds of data and decisions need are needed..

With automated vehicles some of the big problems are having them report back their findings. This is limited by the transmission medium, so, in an AUV, a vehicle may be required to return to some safe transmission point before reporting back. However, if the task has a more detailed set of discriminatory actions, then a knowledge base has to

be expanded to include these data, keeping in mind the cost of memory, time, power, and weight factors.

This bionic model also illustrates how auditory localization can be passively acquired by a very simple set of sensors and effectors. While AUVs don't swallow their prey as the barn owl does, they may want to to take pictures, turn on lights, approach, or avoid. All of these functions can be considered with an awareness of detection, discrimination, and hierarchical sensory information so that decision-making can be left as a straightforward act. Then attention can be directed to learning and changing instructions.

This analytical approach has also aided in identifying areas of information that need to be answered in studies on bionic forms as well as in electro-mechanical simulators. It would be a relatively easy experiment to simulate the relationship of the owl's ear capacities and how information is processed further along the nervous system. Perhaps the inscrutable owl may be worth the challenge.

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BIONIC MODELING OF KNOWLEDGE-BASED GUIDANCE IN
AUTOMATED UNDERWATER VEHICLES

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